MULTIPLE CAVITY LASER ARRAY SOURCE FOR LASER GENERATION OF ULTRASOUND

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INTRODUCTION

A significant expansion of the utility and availability of laser ultrasound as a nondestructive evaluation technique will come as advancements are made to find practical and inexpensive means to improve the detection sensitivity so that it begins to approach more closely the performance of conventional piezoelectric contact ultrasonic methods. Among the several opportunities where technological advances could enhance laser ultrasonic sensitivity, one is the advantageous use of modulated laser array sources to control the nature of the generated ultrasonic signal so that it can be made more readily detectable by optical interferometer receivers. The detection limit of all optimally designed and implemented optical receivers is that imposed by the presence of broadband shot noise so that in every case, the signal-to-noise ratio, SNR, depends upon such parameters as the amplitude of the detected elastic wave, δ, and the bandwidth, B, of the receiving system in the following manner:

$$SNR \propto \frac{\delta}{\sqrt{B}} \tag{1}$$

As can be seen from the equation above, if by some means a laser array source might be used either to increase the signal amplitude or to reduce the signal bandwidth in order that the receiving bandwidth might be correspondingly reduced, one can anticipate an increase in the signal-to-noise ratio corresponding directly to an improvement in overall system detection sensitivity.

Several types of laser array sources have been considered previously by investigators and developers of laser ultrasonic methods. Among these are those requiring time modulation of the laser source [1-6]. In other words, rather than simply requiring a single pulse from the laser, a short burst of repetitive pulses is required. The focus of the work reported here will be in the development and demonstration of a 10-cavity laser array system which can be used to time modulate the laser energy incident either on a single point or an array of points over the surface of a test specimen. Specifically, two types of source arrays will be considered: 1) a single point on the specimen surface excited by a repeated pulse train, and 2) a linear array of excitation points excited sequentially (phased array). For both types of excitation arrays, examples will be shown of signal-to-noise enhancement of both surface waves and bulk longitudinal and shear waves.

LASER SYSTEM DESIGN

A schematic diagram of the 10-laser cavity source system is given in Figure 1. Each laser consists of a 4" long, 1/4" diameter Nd:YAG laser rod mounted in a pump housing with a linear flashlamp. A 60% output coupling mirror and 100% end reflector contain each of the laser cavities. A lithium niobate electro-optic Q-switch assembly is also contained in each cavity. Each laser element is capable of generating a Q-switch pulse of approximately 10 ns duration and in excess of 50 millijoules per pulse. Since in the current system forced air rather than water cooling is used, the repetition rate for each individual laser must be kept below 2 Hz. The pump chambers could be converted to water cooling in order to help increase the pulse repetition rate of each individual laser. Since the system was designed specifically to be a source for laser ultrasonic signals, it was possible to tailor the design in such a way as to help minimize equipment cost. For example, only a single flashlamp power supply and firing circuit is required since all flashlamps are excited at the same time. This is possible since the flashlamps remain "hot" for hundreds of microseconds during which the Q-switches for each cavity can be fired individually to allow a sequence of pulses to be emitted from the system. For the experiments to be described here, the timing circuits for the Q-switch elements were driven by a function generator to insure that the pulse separation from one laser to the next would be uniform and periodic. In the general case, however, the timing circuits could be computer driven so that the lasers might be fired in any arbitrary sequence during a single flashlamp pulse. Using the pulse generator to control the firing sequence, performance below 1 MHz and beyond 25 MHz has been demonstrated. As pulses exit the individual laser elements, the output beams were steered by adjustable mirrors which permitted the beams to be directed either to a common point on the surface of a test specimen or arrayed in any desired pattern. The entire system was mounted on a 2' x 3' optical breadboard and was assembled at a cost just exceeding $50,000. Conventional optical breadboard elements were used to mount each pump chamber and cavity mirror. One can be encouraged, therefore, that with careful engineering design, the entire system could be miniaturized significantly.

EXPERIMENTAL RESULTS

The multi-element laser system was used to implement both a single-point time-modulated ultrasonic source and a linear sequentially excited (phased) laser array source. For both types of sources, the potential signal-to-noise enhancement of surface waves was

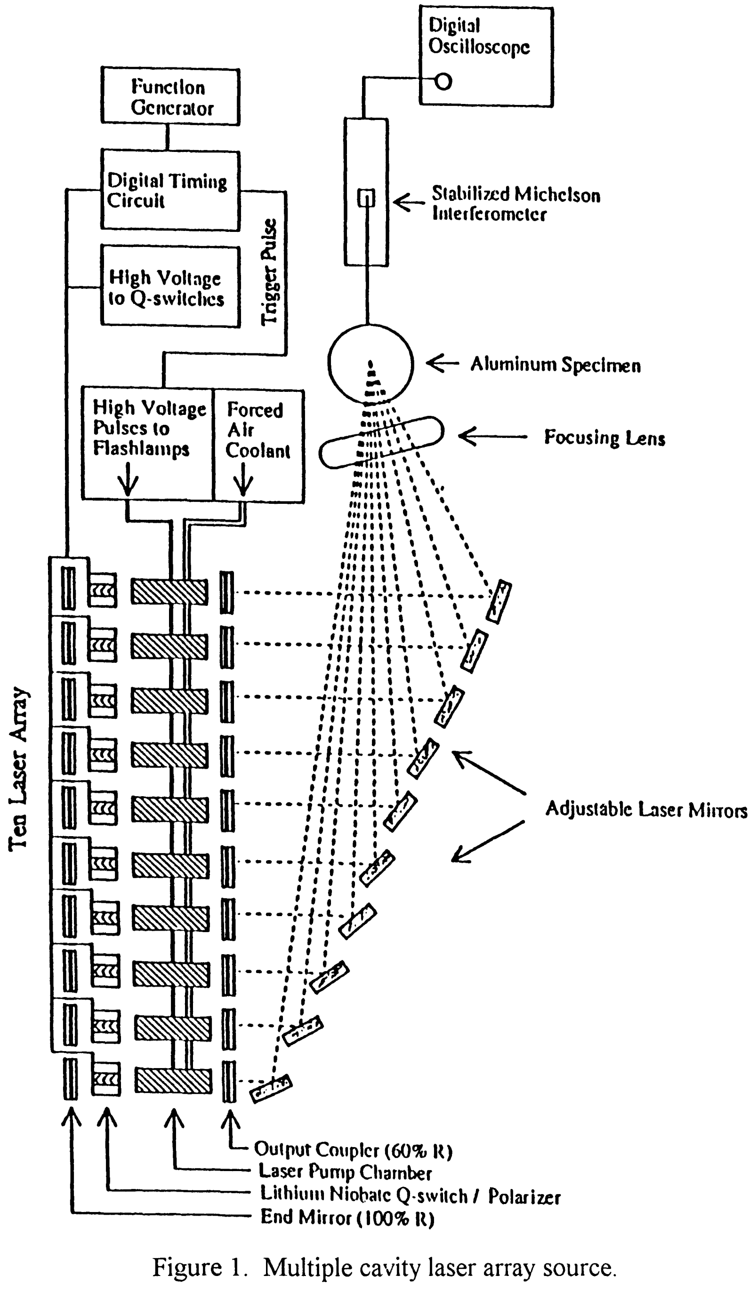

Figure 1. Multiple cavity laser array source.

studied. Consider first the generation of a pulse train of surface Rayleigh wave spikes from a repetatively excited single line source. It is important to note that unlike most other laser generated elastic waves, the out-of-plane displacements of surface Rayleigh waves are bi-polar or bi-phasic in nature. By adjusting the width of each Rayleigh pulse and the time separation between them, it was possible to produce a burst of such pulses so that one followed immediately upon the other without any "dead space" between them. This circumstance was fairly easily obtained using a laser ultrasonic source since the diameter of the laser spot affects directly the width of the Rayleigh spike and the pulse repetition frequency from the laser source determines their time separation. Such optimization of the pulse width and separation was achieved for the Rayleigh pulse train shown in Figure 2a. Note that rather than having the appearance of a sequence of individual spikes, the pulse train appeared as a continuous tone burst. Consequently, in the energy density spectrum for this pulse sequence, the dominant AC component was centered around the 2.8 MHz modulation frequency and higher harmonics were suppressed. As a result, it was possible to use a simple narrowband filter at the 2.8 MHz modulation frequency to help reduce broadband shot noise and thereby enhance signal-to-noise ratio as shown in Figure 2c.

To examine the effect of this kind of laser source on bulk waves, the interferometric detection point was moved to the opposite side of the aluminum sample. The sample itself was 30 mm thick, and the detection point was placed 13 mm off epicenter (24° propagation angle). The interferometrically received waveform is shown in Figure 3a. With the a priori knowledge that the signals of interest have significant spectral content only at 2.8 MHz and the upper harmonics, the filter function, as shown in Figure 3c, could be applied to the noisy signal to extract from it the three tone bursts shown in Figure 3b. The tone burst labelled "1" is not the result of elastic wave generation, but is instead electronic noise resulting from the sequential firing of each of the Q-switches at intervals corresponding to 2.8 MHz repetition rate. Tone bursts "2" and "3," however, correspond to the longitudinal and shear wave arrivals respectively. The several cycles of variation between tone bursts "2" and "3" do not correspond to any expected acoustic wave arrival, but instead are thought to be an artifact of the filtering process.

A second experimental arrangement was used to generate acoustic waves using a laser array of source points separated in space and delayed in time. In this experiment 10 array elements were used, focused to an array of lines perpendicular to the direction of propagation toward the sensor. The width of each line element was approximately 0.1 mm, and each was separated from the other by 0.6 mm. The time separation between excitation of the elements was 200 ns. Figure 4a shows the arrival of a Rayleigh pulse at the receiver location resulting from the excitation of just a single element of the laser array source. Note that the high frequency noise observed early in the trace is the result of electronic interference from the sequential firing of all of the Q-switches in the array system. To produce this trace, all of the Q-switches still were fired, but only one of the optical beams was unblocked to generate a single Rayleigh pulse. When all of the array elements are unblocked, the resulting Rayleigh spike is enhanced considerably, as shown in Figure 4b. It is interesting to note that unlike the case of narrowband generation and detection of sound in which noise is eliminated from the signal, the noise content in the signals shown in Figures 4a and 4b is virtually the same. The

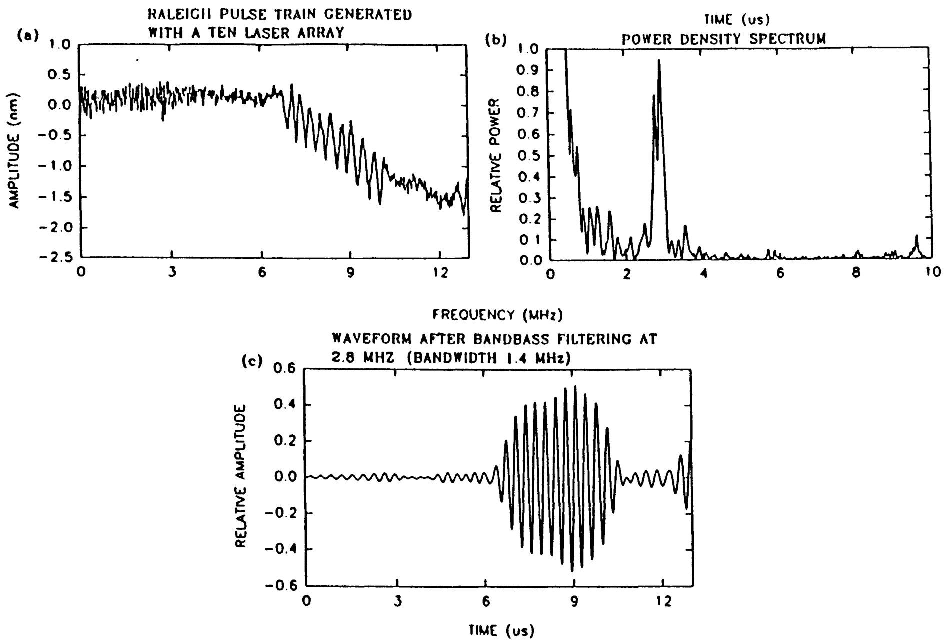

Figure 2. Narrowband generation of surface waves.

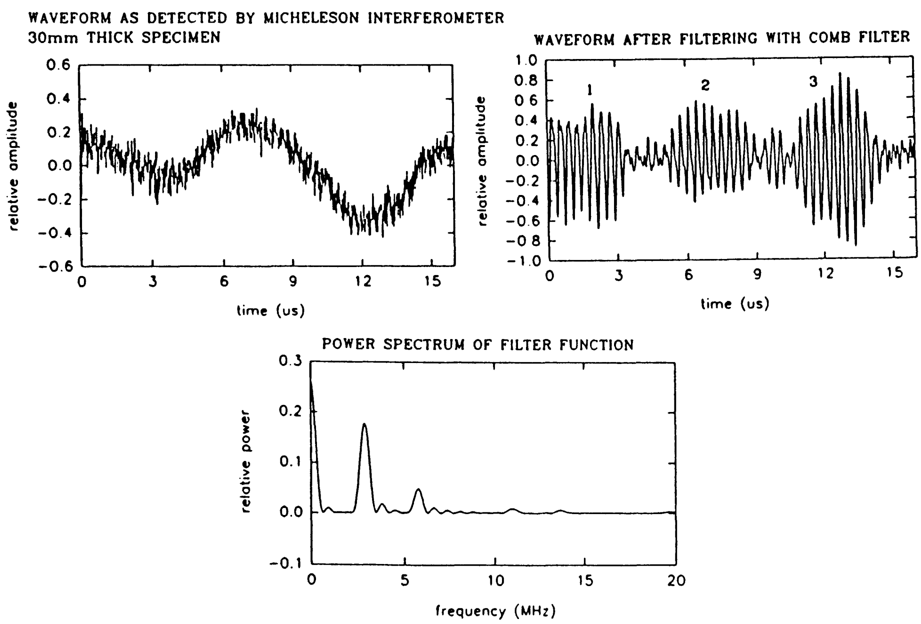

Figure 3. Narrowband generation and filtering for bulk waves.

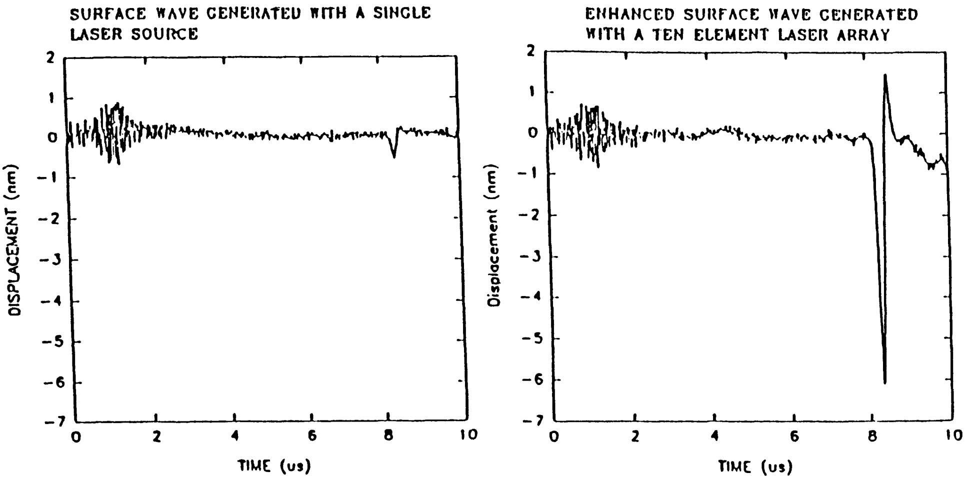

Figure 4. Phased array generation of a Rayleigh surface pulse.

phased array source has served simply to increase the amplitude of the elastic wave displacement, δ, rather than reducing noise by minimizing bandwidth, B.

The final case to be considered is one in which the receiver point was again moved to the opposite side of the specimen from the source location. For this experiment, a 10 mm thick aluminum specimen was used, and the source array spacing adjusted to enhance the arrival of the longitudinal wave spike at a position 9 mm off-epicenter of the array source. The time separation between the excitation of adjacent array elements remained at 200 ns so that the separation between the array spots needed to be adjusted to insure coincidence of the longitudinal arrivals at the receiving point. The total array length was slightly greater than 9 mm. Since the test specimen was only 10 mm thick, the receiving point was well within the near field of the array. As a result, the spacing between the array elements was not made equal. Furthermore, owing to the natural directivity of a thermoelastically-generated longitudinal wave, the efficiency with which longitudinal spikes were generated varied widely over the range of propagation angles from each array element to the receiving point. The fourth element, that lying at about 46^0 with respect to the receiving point, generated a longitudinal displacement with the greatest amplitude in this particular case. All other elements directed longitudinal energy with less efficiency to the receiving point. The waveforms resulting from this array source are shown in Figure 5. Figure 5a shows the arrival resulting from a two-element array. The longitudinal arrival is observed at about 2.7 microseconds with a shear arrival coming at about 4.5 microseconds. As the number of array elements was increased from 2 to 10, a clear enhancement of the longitudinal spike was observed. The shear pulse, however, became broadened and rather distorted, a result to be expected since the array timing was set to optimize the longitudinal wave arrival. Note also that the degree of signal-to-noise enhancement in this bulk longitudinal wave case, using the phased array source, was considerably less than the enhancement observed of the surface

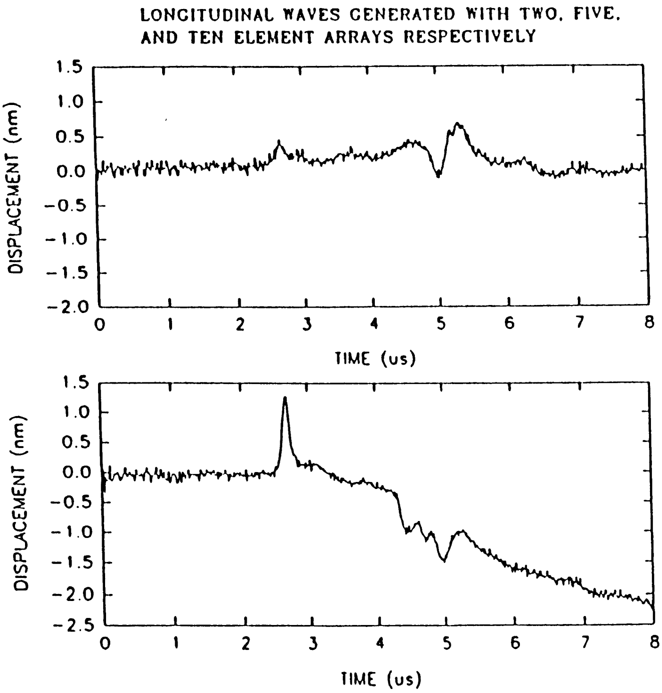

Figure 5. Phased array generation of a bulk longitudinal pulse.

Rayleigh wave. This less dramatic enhancement was, in part, the result of the fact that not all elements, particularly those at low angles, direct strong amounts of longitudinal elastic wave displacements to the receiver point.

CONCLUSIONS

A 10-element multiple head laser array source has been constructed with a capability of providing up to 10 temporally and spatially separated laser beams with energies in excess of 50 millijoules each and pulse durations on the order of 10 ns. Some of the preliminary data generated with this system illustrate the benefits of single point narrowband excitation, both of surface and bulk waves, as well as phased array sources for the enhancement of signal-to-noise ratio of laser generated ultrasonic signals in aluminum specimens. Of particular interest in these preliminary results was the case involving a phased array thermoelastic source of bulk longitudinal waves. In this particular case, the enhancement of the arriving longitudinal spike was considerably less than was observed when a similar array source was used to generate surface Rayleigh waves. This result may be expected when the thickness of the test specimen is on the order of the total extent of the array source. In such cases, the angles between some of the array elements and the receiving point fall outside the range of natural directivity for longitudinal spikes from a surface thermoelastic source. Consequently, little energy is contributed by some of the array elements to the arriving longitudinal spike. Further investigation of this sort of phenomenon and other aspects of laser arrays for efficient generation of ultrasonic signals will be studied in the future using this new multiple element laser array system.

ACKNOWLEDGEMENTS

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